FINAL TECHNICAL REPORT
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Project Title: **EVALUATION OF FGX DRY SEPARATOR FOR CLEANING ILLINOIS BASIN COAL**

ICCI Project Number: 08-1/4.1A-4
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ABSTRACT

The FGX Dry Separator is a density-based separator that has the ability to produce three product streams, i.e. coarse rock, coarse and fine clean coal, and a mixture of middlings particles. Operating forces include gravity, the buoyancy of a fluidized raw coal bed, and the vibration force of the separation deck. Objectives of this study were to investigate the effectiveness of the FGX Dry Separator for removing pure rock from run-of-mine coal producing a low-cost intermediate product that would be a better feed stock for conventional coal preparation plants, and to optimize the FGX Dry Separator performance in terms of ash separation efficiency and sulfur rejection for producing a salable clean coal product without using conventional wet coal preparation processes. A Model FGX-1 Dry Separator with feed throughput capacity of 10 tph was extensively tested at the Illinois Coal Development Park using multiple coal samples having distinctly different cleaning characteristics. Statistically designed experimental programs were conducted to indentify critical process variables and optimize FGX Dry Separator performance by systematic adjustments of critical process variable parameters.

The coal cleaning performance of the FGX Dry Separator was evaluated for the particle size range of 63.5 x 4.76 mm in most cases, although FGX Dry Separator feed consisted of nominal -63.5 mm run-of-mine coals. The best cleaning performance obtained from the FGX Dry Separator is described by specific gravity of separation (SG_{50}) and probable error (Ep) values of 1.98 and 0.17, respectively. These process efficiency measures produced a clean coal with ash content of 13.38% from a feed coal with ash content of 34.45%. Ash content of tailings and middlings streams were 85.09% and 39.57%, respectively. Total sulfur contents of corresponding streams were 3.87%, 4.68%, 6.87%, and 4.62%. For a relatively easy to clean Springfield Coal (Cleaning Index: 0.72), only about 0.42% of the clean coal (i.e., 1.6 float fraction) present in the feed was lost to the tailings stream. For a relatively difficult to clean Knight Hawk Coal (Cleaning Index: 0.53), about 0.98% of the clean coal present in the feed was lost to the tailings stream.

A preliminary economic analysis indicates that total capital, installation, and operating costs for cleaning Illinois coal using the FGX Dry Separator will be $0.91/ton of raw coal and $1.56/ton of clean coal. The operating cost alone is estimated to be $0.69/ton of raw coal and $1.19/ton of clean coal.

EXECUTIVE SUMMARY

A majority of the coal produced in Illinois is extracted from underground mines, where a minimum working height of six to eight feet is typically desired for the safe and easy maneuverability of machinery and miners. To maintain this height, particularly in cases of relatively thin coal seams, a significant amount of pure solid inert material is mined along with the coal seam. This material is commonly a shale rock present above and/or below the seam. In addition, in cases where the coal seam is somewhat undulating, a significant amount of rock is mined to develop relatively flat floor and roof surfaces to facilitate the installation of mine infrastructure such as conveyor belts and to enable easy and safe mining operations. This inert rock, which is referred as out-of-seam dilution, amounts to between 10% and 30% of the raw coal produced from a typical underground coal mine in Illinois. Understandably, the presence of these rocks dilutes the quality of raw coal entering coal preparation plants negatively impacting plant yield, i.e., the percentage of plant feed recovered in the plant product. Furthermore, these rocks undergo a gradual size-degradation as raw coal passes through conveyor transfer chutes, rotary breakers, and scalping screens before they enter the preparation plant. Once in the plant where slurries are used in almost every unit operation, claystone shales suffer significant deterioration when it comes in contact with water. This phenomenon tends to produce a fine slime material, which renders the coal cleaning, especially in the fine particle size range, much more difficult. The presence of fine slimes in the coarse coal circuit also affects the viscosity of the dense medium and tends to increase the loss of magnetite used to make the dense medium to the plant tailings stream. Thus, negative impacts of out-of-seam dilution in run-of-mine coal are many fold.

To reduce the amount of out-of-seam dilution, new mining technologies such as horizontal controls and interface sensors are being studied by other investigators. The present study concentrated on developing a technology for separating and removing high-density shale material (pure rock) from raw coal before it enters the coal preparation plant. The technology chosen for evaluation is known as the FGX Dry Separator. It is a relatively new dry separation technology that appears to have great promise and cost effectiveness. There have been more than 800 new installations, including one in the US, of this technology within eight years of its being commercialized in China. The FGX Dry Separator consists of a vibratory feeder, a separating deck and vibrator, air chambers, and a hanging support mechanism. A density-based separation is achieved under the action of a combination of forces. These forces include gravity, buoyancy of an autogenous medium, vibration, upward airflow, and inter-particle friction.

The focus of this study was two-fold. One was to investigate the effectiveness of the FGX Dry Separator for removing pure rock from run-of-mine coals to produce an intermediate product that can serve as a better feed stock for conventional coal preparation plants. The other was to optimize the FGX Dry Separator for achieving the best ash separation efficiency and sulfur rejection performance enabling its application in place of conventional wet coal preparation processes to produce a salable clean coal product. FGX SepTech, LLC, the exclusive distributor of the FGX Dry Separator in the US, contributed significantly to this study by making available their Model FGX-1 Dry

Separator with feed throughput capacity of 10 tph for the experimental program. The test work was conducted at the Illinois Coal Development Park using multiple coal samples having distinctly different cleaning characteristics. Coal suppliers and users that expressed interest in this study by supplying coal samples from their operations included Knight Hawk Coal Company, Peabody Energy, Springfield Coal Company, Southern Illinois Power Cooperative (SIPC), and Phoenix Coal Company. Initially, a statistically designed Plackett and Burman experimental program was conducted to indentify which of the eight known operating variables of the FGX Dry Separator are critical. Four process variables were identified as such. They are feeder frequency, deck vibration frequency, longitudinal deck angle, and baffle plate height. These variables were investigated in further detail using a Central Composite Design to achieve the highest tailings ash content, ash separation efficiency, and sulfur rejection performance from the FGX Dry Separator.

The coal cleaning performance of the FGX Dry Separator was evaluated in the particle size range of 63.5 x 4.76 mm in most cases, although some FGX Dry Separator feed consisted of nominal -63.5 mm run-of-mine coal. The best cleaning performance obtained from the FGX Dry Separator is described by a SG_{50} and Ep value of 1.98 and 0.17, respectively, for the entire +4.76 mm size coal. SG_{50} and Ep values for individual size fractions were as follow: 1.90 and 0.12 for 63.5 x 50.8 mm size coal; 1.95 and 0.18 for 50.8 x 25.4 mm size coal; 2.01 and 0.19 for 25.4 x 12.7 mm size coal; 2.03 and 0.23 for 12.7 x 4.76 mm size coal. With these process efficiency measures, a product with clean coal ash content of 13.38%, tailings ash content of 85.09%, and middlings ash content of 39.57% was produced from a feed coal with ash content of 34.45%. Total sulfur content of feed, clean coal, middlings, and reject streams were 4.68%, 3.87%, 4.62%, and 6.87%, respectively. Increasing the proportion of fines (i.e., -4.76 mm size material) in the feed significantly improved FGX Dry Separator cleaning performance, which was expected. However, the highest ash separation efficiency and sulfur rejection were achieved at different levels of fine content (29% versus 18%) in the feed. A limited number of tests conducted with the relatively fine (93% -4.76 mm particle size) SIPC sample indicated that a reasonably good level of ash and sulfur cleaning could be achieved by the FGX Dry Separator even below a particle size of 4.76 mm. For the relatively easy to clean Springfield Coal sample (Cleaning Index: 0.72), only about 0.42% of clean coal (i.e., 1.6 float fraction) present in the feed was lost to the tailings stream. For the relatively difficult to clean Knight Hawk Coal sample (Cleaning Index: 0.53), about 0.98% of clean coal was lost to the tailings stream.

A preliminary economic analysis conducted for cleaning 100 tph of a typical Illinois coal based on the recent US installation experience indicates an initial capital and installation cost investment of $882,000. Based on estimated annual revenue of $10.45 million, the pay-back period was calculated to be approximately one month. Total ownership and operating costs for cleaning Illinois coal with the FGX Dry Separator is estimated to be $0.91/ton of raw coal and $1.56/ton of clean coal. The operating cost alone is estimated to be $0.69/ton of raw coal and $1.19/ton of clean coal. These cost estimates compare very favorably with relevant wet separation processes, which have operating costs in the range of $1.00-1.50/ton of raw coal and $1.50-2.00/ton of clean coal.

OBJECTIVES

The main goal of this study was to examine the effectiveness of the FGX Dry Separator for cleaning/deshaling Illinois coal. Toward this goal, specific project objectives were:

- Testing bulk samples obtained from Illinois coal mines and power plants in the FGX Dry Separator to determine the feasibility of commercializing the technology in Illinois.
- Generating characteristic partition data describing the FGX Dry Separator's performance efficiency for coals with different cleaning characteristics.
- Conducting an economic analysis to evaluate the capital ($/tph of installed capacity) and operating cost ($/ton of raw and clean coal) for the FGX Dry Separator technology.

INTRODUCTION AND BACKGROUND

Air-tables (Arnold et al., 2003), Allair Jigs (Kelly and Snobby, 2002; Weinstein and Snobby, 2007), and air-dense medium fluidized bed technology (Luo et al., 2003) are some of the dry separation technologies that come to mind when dry coal cleaning is talked about. The Allair Jig has been commercialized in the US with the first 50 tph unit installed at an Ohio surface coal mine in 2001. The system provides high density cut-points as required in rock-removal operation; however the unit is only moderately efficient and the top particle size that it can treat is only 2 inches (50.8 mm).

The FGX Dry Separator is a special type of air-table that consists of a perforated separating deck, three air chambers, a vibrating mechanism, and a hanging support mechanism as shown in Figure 1. The separating deck, having riffles on its surface, is suspended in an inclined position both in the longitudinal and transverse directions as shown. Airflow supplied from a blower fluidizes feed material on the deck and the vibration mechanism imparts a helical turning motion to particles as they slide towards the refuse end. Particle stratification on the separating deck takes place under the action of the vibration mechanism and the fluidizing force of the air flow. Under the action of the vibration force alone, coarser particles of lower density are stratified in the upper layer and finer coal having lower density moves to the bottom of the bed. On the other hand, under the action of the upward airflow alone, finer particles are blown to the upper layer irrespective of particle density. Thus, with a suitable combination of vibration force and the upward pressure of airflow, stratification of solids can be achieved mainly based on their differences in density, as illustrated in Figure 2. As a result, a bed of high density refuse and pyrite particles is formed on the bottom-most layer, or in other words, the layer closest to the deck surface. The buoyancy effect produced by the interaction of heavier particles can effectively control the misplacement of low density coal particles into the refuse bed, thus ensuring the purity of the refuse stream (Lu et al., 2003).

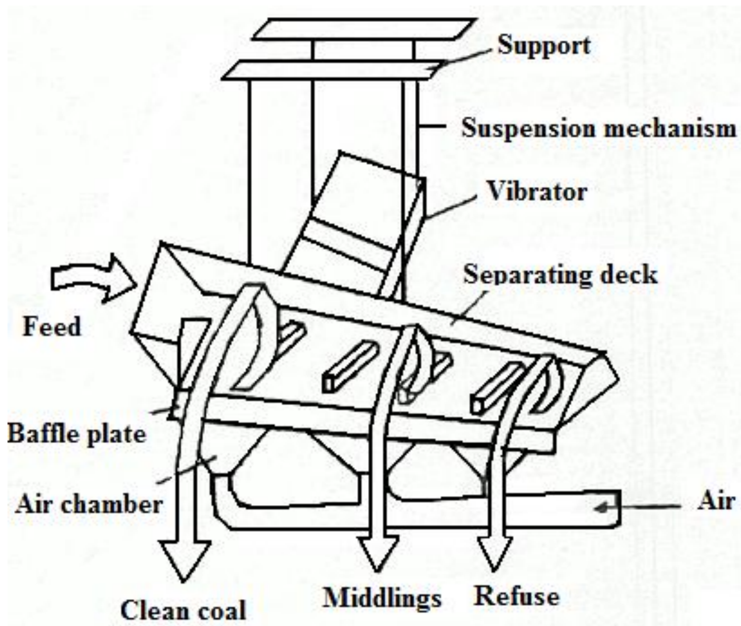


Figure 1: A schematic diagram of the FGX Dry Separator showing the different product streams (Lu et al., 2003).

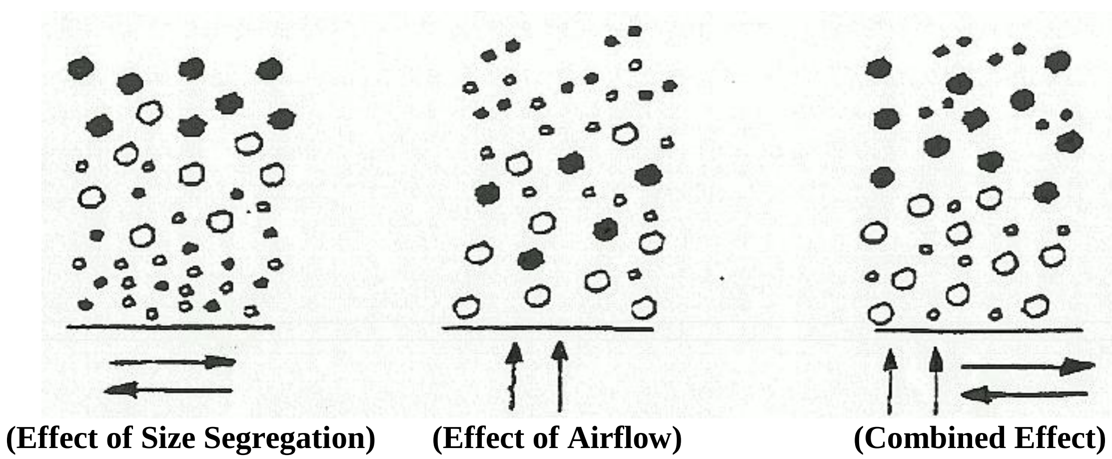


Figure 2: Stratification of feed material on the separating deck under combined effects of vibration and upward air pressure. Empty particles represent heavier solids (refuse) and solid particles represent lighter solids (clean coal) (Lu et al., 2003).

Past results obtained on Chinese coal (Lu et al., 2003), and a recent study conducted by Honaker et al. (2007) on several U.S. coal samples, indicates the high efficiency density-based separation achievable from the FGX Dry Separator. High efficiency dry separation combined with low cleaning costs has resulted in the FGX Dry Separator becoming vastly popular in China with nearly 800 installations in the last eight years.

The main goal of the present study was not only to deshale (remove pure rock) raw coal extracted from Illinois mines but also to assess the maximum ash separation efficiency and sulfur rejection achievable using the FGX Dry Separator for cleaning raw coals of varying cleaning characteristics. A Model FGX-1 Dry Separator, having a maximum feed handling capacity of 10 tph, was extensively tested at the Illinois Coal Development Park using coal samples from five different sources.

EXPERIMENTAL PROCEDURES

FGX SepTech, LLC, the sole source supplier of FGX Dry Separators in the US, supplied the Model FGX-1 test unit shown in Figure 3. A schematic diagram of the test unit is shown in Figure 4. Testing was carried out using a Bobcat front end loader to introduce raw coal to the feed hopper as shown in Figure 5. Initial testing was conducted to develop a good working knowledge of the FGX Dry Separator operation and to optimize process parameter values. A single coal sample collected from the Knight Hawk Coal Company was used for those tests. Additional samples were collected from Springfield Coal Company, Southern Illinois Power Cooperative (SIPC), Peabody Energy, and Phoenix Coal Company for testing the commercial applicability of the FGX Dry Separator to a variety of coals. Details of experimental conditions utilized for each coal sample are discussed under Task 2 of the following section of this report.

Figure 3: Model FGX-1 Dry Separator supplied by FGX SepTech, LLC.

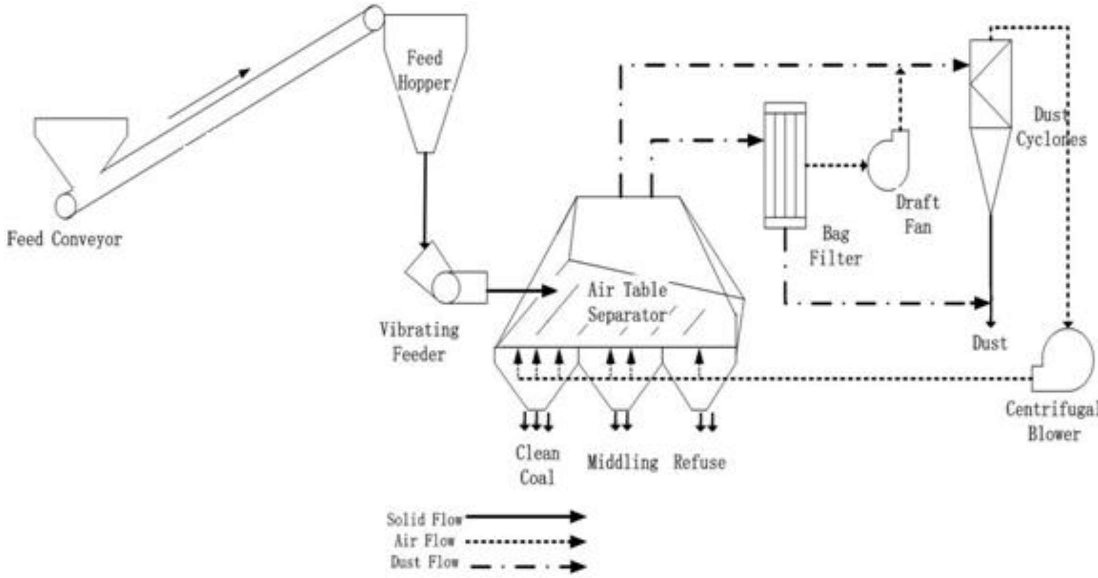


Figure 4: A schematic diagram of the FGX-1 Dry Separator test unit.

Figure 5: FGX Dry Separator testing at Southern Illinois University's Illinois Coal Development Park in Carterville, Illinois.

RESULTS AND DISCUSSIONS

Task 1: Sample Collection, Preparation, and Characterization

A total of five different bituminous coal samples were utilized in this study to evaluate the cleaning efficiency achievable using the FGX Dry Separator. Approximately 15 tons of run-of-mine coal collected from Knight Hawk Coal Company's Prairie Eagle Mine was used to do an extensive study with the FGX Dry Separator. Upon completion of a thorough evaluation of the optimum ash and sulfur cleaning performance achievable from the FGX Dry Separator for the Knight Hawk Coal sample, more coal samples (in smaller quantities) were collected from three different Illinois coal mines/utilities operated by Springfield Coal Company, Peabody Energy, and Southern Illinois Power Cooperative (SIPC), respectively. An additional coal sample was collected from a coal mine in Oklahoma operated by Phoenix Coal Sales, Inc.

Representative bucket samples were collected for the size-by-size characterization of total mass, ash content, and sulfur content distributions for all five coal samples. Results are given in Table 1. As shown in Table 1, the Springfield Coal sample contained a very low proportion of fine coal (-4 mesh or 4.76 mm size fraction), whereas the Knight Hawk Coal sample contained as much as 42.71% fines. The SIPC sample was the finest, having a -4.76 mm size fraction of nearly 93%. Overall ash content for all coal samples varied from a low of 20.44% for the SIPC sample to a high of 40.23% for the Springfield Coal sample. Total sulfur content varied from a low of 2.92% for the SIPC sample to a high of 6.22% for the Phoenix Coal sample.

Table 1: Distribution of mass, ash and total sulfur in samples utilized for FGX Dry Separator tests.

Coal Samples		Knight Hawk Coal	Springfield Coal	Phoenix Coal	Peabody Energy	SIPC
Weight %	+4.76 mm	57.29	91.42	78.76	68.07	
	-4.76 mm	42.71	8.58	21.24	31.93	
	Total	**100**	**100**	**100**	**100**	
Ash %	+4.76 mm	25.39	39.14	25.83	23.75	
	-4.76 mm	36.80	51.84	35.73	32.55	
	Total	**30.26**	**40.23**	**27.93**	**26.56**	
Sulfur%	+4.76 mm	3.80	4.49	6.79	4.11	
	-4.76 mm	3.50	3.89	4.09	3.21	
	Total	**3.67**	**4.44**	**6.22**	**3.82**	
Weight %	+1.0 mm					48.62
	-1.0 mm					51.38
	Total					**100**
Ash %	+1.0 mm					23.93
	-1.0 mm					17.14
	Total					**20.44**
Sulfur%	+1.0 mm					3.05
	-1.0 mm					2.80
	Total					**2.92**

Coal samples were manually screened to prepare the recommended 63.5 x 3.0 mm particle size fractions to be fed to the FGX Dry Separator. This significantly reduced the amount of -4.76 mm size coal in the actual feed stream reporting to the FGX Dry Separator. Ash and sulfur rejection achievable from the FGX Dry Separator were evaluated only for the 63.5 x 4.76 mm size fraction with one exception. The SIPC sample was extremely fine and hence the bottom size was lowered to 1 mm. This provided an opportunity to test the FGX Dry Separator's performance below its conventional particle size range.

Float/sink analyses were conducted on feed samples for two different coals having significantly different cleaning characteristics. Results are shown in Table 2. A simple analysis of float/sink data for Knight Hawk Coal and Springfield Coal samples indicates that coal cleaning indices (the ratio of 1.3 float and 1.6 float) for both coals are 0.53 and 0.72, respectively. The lower Cleaning Index for the Knight Hawk Coal sample indicates a relatively more difficult cleaning characteristic, which was also evidenced from its cleaning performance obtained by the FGX Dry Separator.

Table 2: Washability data from float/sink analyses of the -2.5-inch size fraction of two major coal samples utilized in this study.

Specific Gravity	**Springfield Coal**		**Knight Hawk Coal**	
	Weight%	Ash%	Weight%	Ash%
Float 1.3	53.86	10.61	42.57	5.60
-1.3+1.4	10.57	15.51	16.94	10.20
-1.4+1.5	8.51	19.34	17.27	15.88
-1.5+1.6	2.25	29.37	3.71	22.94
-1.6+1.8	2.33	41.15	2.86	35.38
-1.8+2.0	1.62	56.92	2.70	57.80
-2.0+2.2	1.14	72.83	2.25	77.55
2.2 Sink	19.74	92.00	11.70	82.05
Total	**100.0**	**30.53**	**100.0**	**21.62**

Task 2: FGX Dry Separator Testing

A Model FGX-1 Dry Separator test unit having a feed throughput capacity of 10 tph was supplied by the equipment vendor, FGX SepTech, LLC for this project. Testing was carried out at the Illinois Coal Development Park operated by Southern Illinois University (SIU) using the general experimental layout illustrated in the schematic diagram of Figure 4.

The FGX Dry Separation technology was new to SIU's coal preparation research group. Therefore, it was desired to conduct several series of exploratory experiments to get a better understanding of various process parameters and the nature of their effects on important process responses, such as combustible recovery, ash rejection, and sulfur rejection. As indicated in Table 3, seven series of tests were conducted using the Knight

Hawk Coal sample by varying one parameter at a time. For example, for Test Series 1, five tests were conducted by varying the feeder frequency over the range of 50 to 90 Hz while keeping other operating parameters at their standard levels. After obtaining a good understanding of parameter ranges, a Plackett and Burman experimental program was utilized to indentify the most critical process variables among the eight listed in Table 4. Based on these test findings, a Central Composite Design consisting of 28 tests was pursued by varying the four most critical process variables (listed in Table 5) to optimize ash and sulfur cleaning performance achievable from the FGX Dry Separator. Then, the four remaining coal samples were tested using process parameter values listed in Table 6.

Table 3: Operating parameter values utilized during exploratory tests conducted using the Knight Hawk Coal sample in the FGX-1 test unit at the Illinois Coal Development Park.

Test Series	Feeder Frequency (Hz)	Longitudinal Angle (deg.)	Deck Vibration Frequency (Hz)	Baffle Plate Height (cm)	Clean Coal Air Valve	Lateral Angle (deg.)	Clean Coal Splitter Position	Refuse Splitter Position
1	50 to 90	1	90	0	Full Open	7.5	P3	R2
2	70	1	60 to100	0	Full Open	7.5	P3	R2
3	70	1	90	0	Full Open	7.5	P1-P5	R2
4	70	1	90	0	Half Open - Full Open	7.5	P3	R2
5	70	1	90	0 to 1.9	Full Open	7.5	P3	R2
6	70	-1.5 to +2.5	90	0	Full Open	9.0	P3	R2
7	70	1	90	0	Full Open	4.5-9	P3	R2

Table 4: List of operating parameters used for the Plackett and Burman experimental design with the Knight Hawk Coal sample.

Factor	Name	Units	Type	Low Actual	High Actual
1	Feed Frequency	Hz	Numeric	60	90
2	Bed Frequency	Hz	Numeric	80	100
3	Clean Coal Splitter	not applicable	Categoric	Low	High
4	Refuse Splitter	not applicable	Categoric	Low	High
5	Clean Coal Air	not applicable	Categoric	Half Open	Fully Open
6	Baffle Plate Height	cm	Numeric	0	1.9
7	Lateral Deck Angle	degree	Numeric	5	8.5
8	Longitudinal Deck Angle	degree	Numeric	-1	1

Table 5: List of operating parameters used for the Central Composite experimental design with the Knight Hawk Coal sample.

Factor	Name	Units	Type	Low	Medium	High
1	Feeder Frequency	Hz	Numeric	60	70	80
2	Longitudinal Angle	degree	Numeric	-1	0	1
3	Vibration Frequency	Hz	Numeric	80	90	100
4	Baffle Plate Height	cm	Numeric	0	1.6	3.2

Table 6: List of operating parameters used for additional four coal samples tested in the FGX Dry Separator.

Factor	Name	Units	Type	Low Level	High Level
Springfield Coal					
Factor	Name	Units	Type	Low Level	High Level
1	Feeder Frequency	Hz	Numeric	60	90
2	Deck Vibration Frequency	Hz	Numeric	80	90
3	Longitudinal Deck Angle	Degree	Numeric	-1	2.8
Peabody Coal					
Factor	Name	Units	Type	Low Level	High Level
1	Feeder Frequency	Hz	Numeric	60	80
2	Deck Vibration Frequency	Hz	Numeric	90	100
3	Longitudinal Deck Angle	Degree	Numeric	0	1
SIPC					
Factor	Name	Units	Type	Low Level	High Level
1	Feeder Frequency	Hz	Numeric	50	70
2	Deck Vibration Frequency	Hz	Numeric	70	90
3	Clean Coal Air Opening		Categoric	Minimum	Half Open
4	Longitudinal Deck Angle	Degree	Numeric	-1	1
5	Tailings Splitter Position		Categoric	Minimum	Maximum
Phoenix Coal					
Factor	Name	Units	Type	Low Level	High Level
1	Feeder Frequency	Hz	Numeric	70	80
2	Deck Vibration Frequency	Hz	Numeric	80	90
3	Lateral Deck Angle	Degree	Numeric	6	7
4	Longitudinal Deck Angle	Degree	Numeric	-1	1

Task 3: Sample and Data Analysis from FGX Dry Separator Testing

Task 3.1 Exploratory Test Results

Exploratory FGX Dry Separator experiments were conducted using the traditional approach of "varying one parameter at a time." Figure 6 illustrates the ash cleaning performance obtained for the +4.76 mm size fraction of all 32 tests conducted in seven test series. The Test # shown in Figure 6 represents the Test Series # shown in Table 3. Two test results that stand out by exhibiting more than 40% separation efficiency were obtained at the lowest feed rate (i.e., feeder frequency ~ 50 Hz).

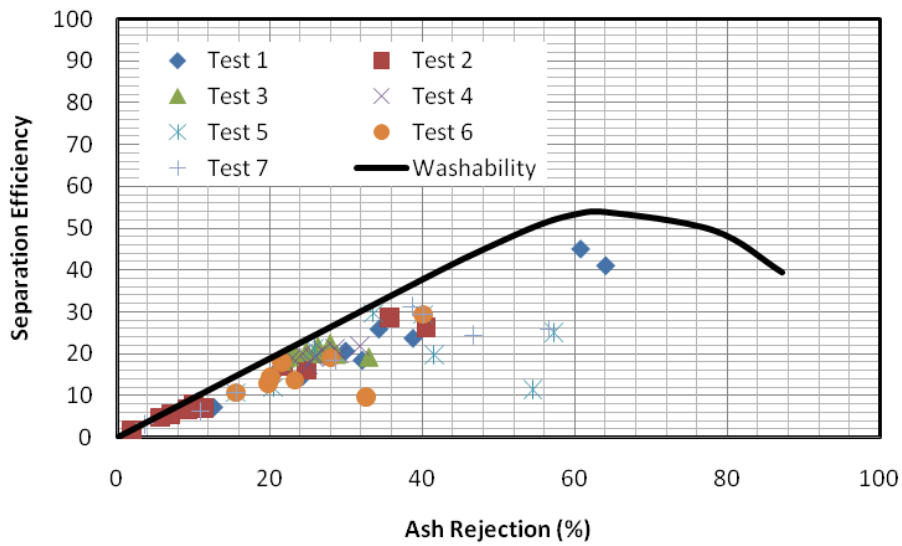


Figure 6: Ash cleaning performances for seven series of exploratory tests conducted with the Knight Hawk Coal sample. Test # represents Test Series # in Table 3.

As revealed in Figure 7(a), the clean coal yield obtained by the FGX Dry Separator increased with increasing feeder frequency due to the concomitant increase in feed rate. A full bed of materials is needed on the FGX Dry Separator deck for a good transverse material flow to the clean coal ports. The Model FGX-1 Dry Separator performed well up to a frequency of 90 Hz, the maximum level tested. This frequency corresponds to the designed feed capacity of 10 tph. However, at this frequency, the actual feed rate to the test unit was measured at just more than 8 tph. These tests also found that tailings ash content reduced significantly with increasing feed rate. This may be due to increasing misplacement of coarse clean coal to the reject stream at higher feed rates.

Figure 7(b) indicates that clean coal yield decreased gradually with increasing vibration frequency of the FGX Dry Separator deck; however, tailings ash content remained approximately constant. It is believed that high vibration frequency resulted in lower height of the throw (amplitude). This phenomenon impeded the material “jump” rate to the clean coal port. The longer the time material spent on the deck, the greater the probability of it reporting to the tailings port resulting in lower clean coal yield.

Clean coal splitter position can be adjusted from right to left to widen the section of material on the deck reporting to the clean coal port. Splitter Position 1 in Figure 7(c) represents the widest opening for the clean coal port, whereas Position 5 represents the narrowest opening. As shown, the clean coal yield reduced significantly at Position 5 with a commensurate decrease in tailings ash content due to understandable reasons.

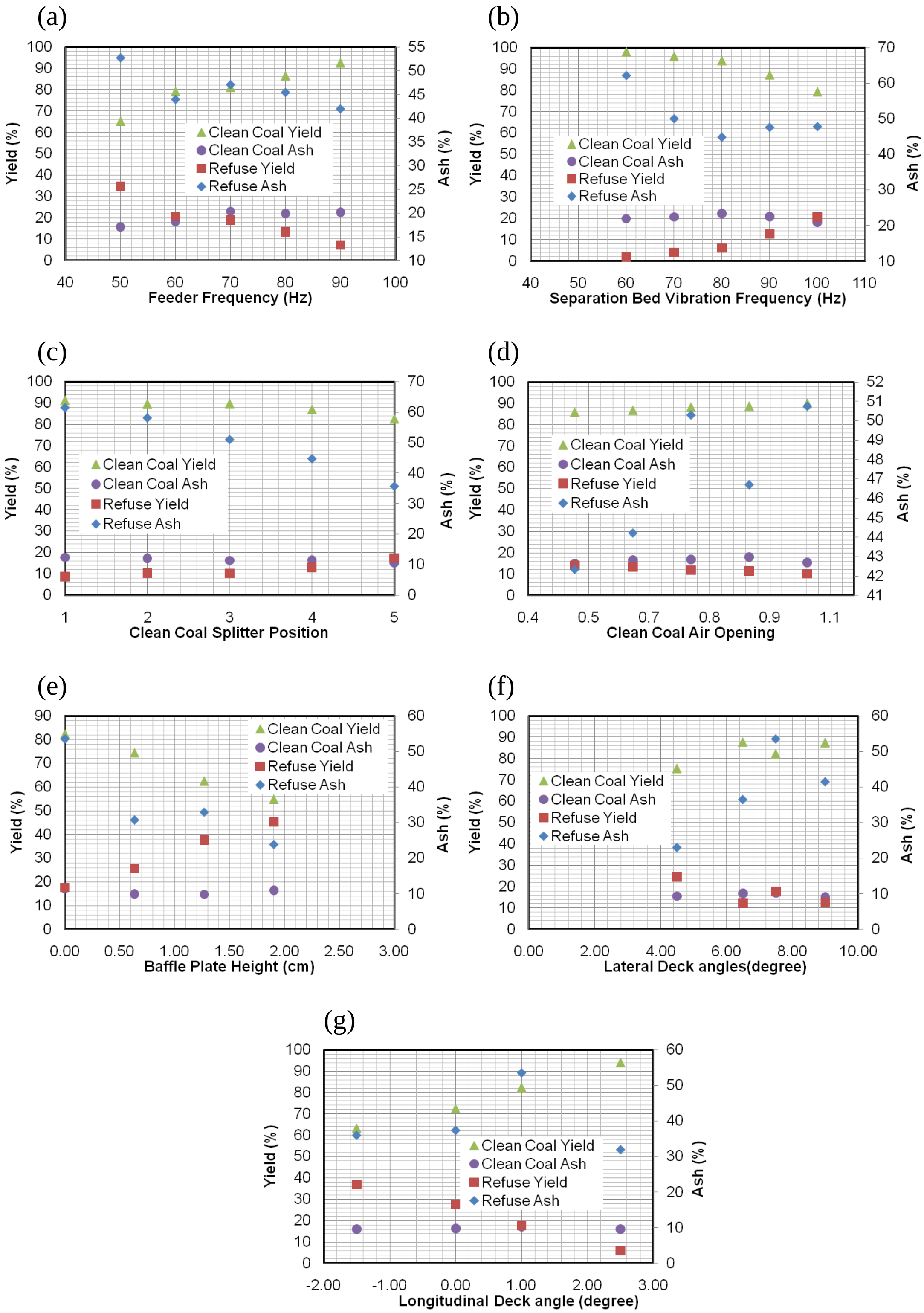


Figure 7: Preliminary investigation of FGX Dry Separator parametric effects during the exploratory test program.

The effect of fluidization air blown from underneath the deck on FGX Dry Separator performance is illustrated in Figure 7(d). As shown, increasing fluidization air did not result in any appreciable change in the clean coal yield; however tailings ash content increased significantly with an increased level of bed fluidization due to improvement in material selectivity.

Figure 7(e) reveals the effect of increasing gate (baffle plate) height at the clean coal section of the deck. Increased gate height restricted the ready flow of coal to the clean coal port thus affecting clean coal yield and refuse ash content.

Increasing lateral deck angle made it easier for coal to flow across the deck to the clean coal port. This phenomenon resulted in increased clean coal yield and increased tailings ash content at the highest lateral deck angle, as indicated in Figure 7(f). Increasing longitudinal deck angle impeded material flow along the deck towards the tailings port, resulting in increased coal yield at the clean coal port and high tailings ash content, as shown in Figure 7(g).

Task 3.2 Plackett and Burman Experimental Program

A Plackett and Burman experimental design was utilized to indentify the most critical FGX Dry Separator process parameters. Experimental conditions for twelve tests varying eight process parameters and resulting ash cleaning performance are listed in Table 7. These data were statistically analyzed to develop corresponding half-normal probability plots (Figure 8) for four responses. As marked in Figures 8(a) and 8(b), longitudinal deck angle (Factor H) and feeder frequency (Factor A) were the most critical process parameters for ash separation efficiency, which is a function of combustible recovery and ash rejection. Figure 8(c) indicates the importance of feeder frequency (Factor A) and baffle plate height (Factor F) for the product ash response. Figure 8(d) shows that longitudinal deck angle (Factor H) and deck vibration frequency (Factor B) are critical for the tailings ash response. Based on these findings, Factors A, B, F, and H were further evaluated in a more detailed study for optimizing FGX Dry Separator performance.

Task 3.3 Optimization Test Program

After indentifying four critical process parameters in Task 3.2, a Central Composite Design (CCD) was utilized to optimize FGX Dry Separator ash and sulfur cleaning performance. Experimental conditions for 28 CCD tests and resulting ash and sulfur cleaning performance are listed in Table 8. Statistical perturbation plots of these tests, shown in Figure 9, revealed the relative importance of the four key process parameters on various ash and sulfur cleaning process responses. Two parameters, feeder frequency and baffle height, had a significant effect on product ash response, whereas longitudinal angle had the most significant effect on tailings ash content. Feeder frequency and deck vibration frequency played the most significant role in affecting ash separation efficiency, whereas longitudinal deck angle affected the sulfur rejection response the most.

Table 7: Operating conditions and ash cleaning results from the Plackett and Burman experimental program where P, M, and R refer to concentrate, middlings, and refuse streams, respectively.

Test #	Feeder Frequency (Hz)	Deck Vibration Frequency (Hz)	Clean Coal Splitter Position	Refuse Splitter Position	Clean Coal Air Valve	Baffle Plate Height (cm)	Lateral Deck Angle (˚)	Longitudinal Deck Angle (˚)	Product Ash (%)	Refuse Ash (%)	Combustible Recovery (P+M) (%)	Ash Rejection (R) (%)
1	90	85	High	High	Half	10.00	5.0	-1	16.49	30.09	87.94	22.75
2	90	101	High	Low	Full	10.00	5.0	1	14.71	49.81	75.56	63.43
3	60	85	Low	Low	Half	8.25	5.0	-1	12.29	23.74	69.20	49.36
4	90	85	High	Low	Half	8.25	8.5	1	10.81	28.90	54.74	73.36
5	60	101	High	High	Half	10.00	8.5	-1	17.44	23.45	86.83	19.60
6	60	85	Low	High	Full	10.00	5.0	1	15.46	33.05	93.50	16.11
7	60	85	High	High	Full	8.25	8.5	1	16.75	57.91	97.94	11.70
8	90	101	Low	High	Half	8.25	5.0	1	14.54	59.04	97.36	16.69
9	60	101	High	Low	Full	8.25	5.0	-1	19.41	50.66	98.15	7.49
10	90	101	Low	High	Full	8.25	8.5	-1	15.98	61.32	98.83	8.83
11	90	85	Low	Low	Full	10.00	8.5	-1	16.38	58.19	95.25	25.97
12	60	101	Low	Low	Half	10.00	8.5	1	12.12	52.72	96.03	19.47

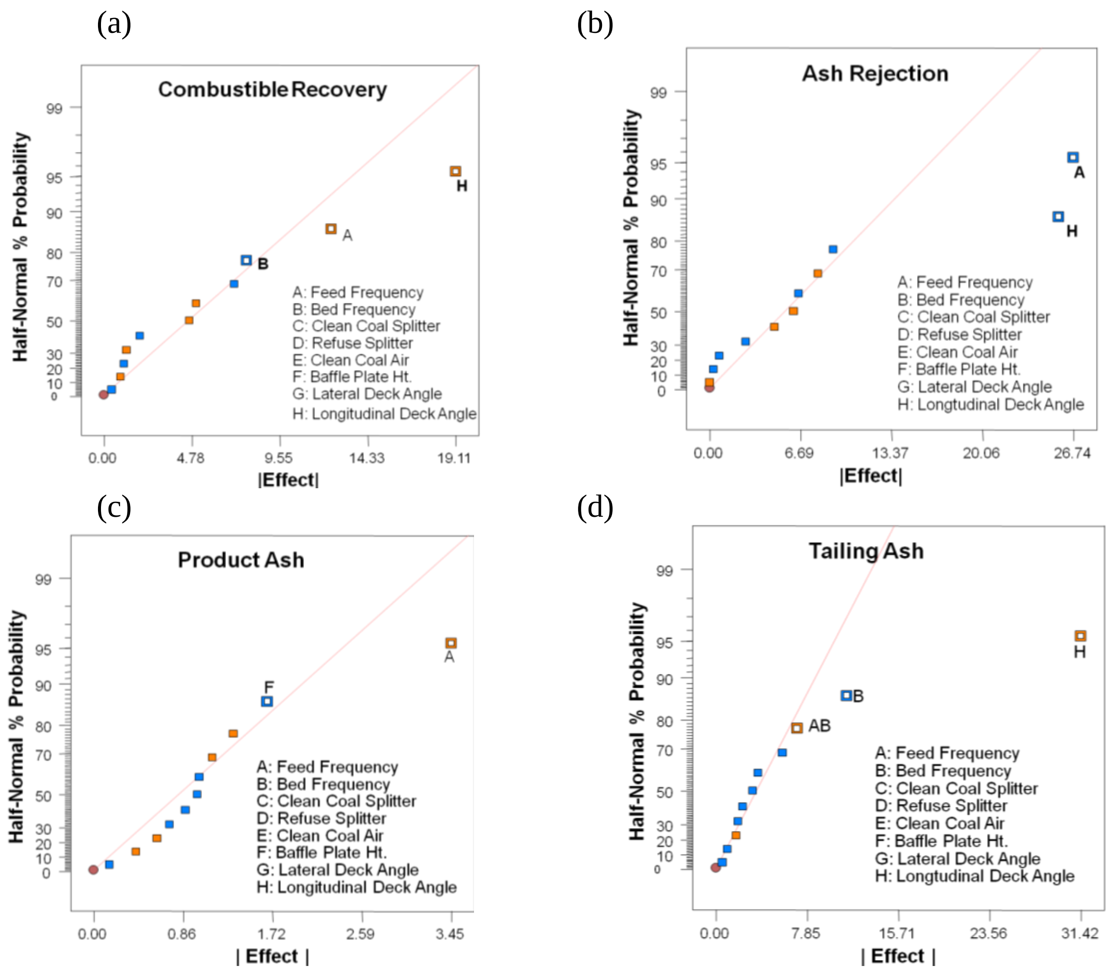


Figure 8: Half-normal probability plots generated from the Plackett and Burman experimental program identifying critical process parameters for the FGX Dry Separator.

Table 8: Operating conditions and resulting ash and sulfur cleaning performance obtained from the optimization test program where A is feeder frequency (in Hz), B is longitudinal deck angle (in degrees), C is bed frequency (in Hz), D is baffle plate height (in cm), and P, M, and R refer to concentrate, middlings, and refuse streams, respectively.

CCD Design ID	A	B	C	D	Feed Ash (%)	Product Ash (%)	Middlings Ash (%)	Refuse Ash (%)	Combustible Recovery (P+M) (%)	Ash Rejection (R) (%)	Sulfur Rejection (R) (%)
1	60	-1	80	3.2	21.07	11.21	16.49	30.28	68.57	51.13	45.65
2	70	0	90	1.6	19.01	14.42	13.60	37.88	84.21	41.03	28.33
3	70	0	90	1.6	19.73	13.94	16.32	39.47	85.47	38.54	29.74
4	80	1	100	0	14.66	12.38	21.55	59.06	98.78	10.24	4.71
5	70	0	80	1.6	18.58	13.84	16.27	43.12	90.34	32.10	23.76
6	60	1	100	3.2	18.72	11.25	14.84	46.04	91.00	33.32	20.88
7	70	0	90	0	19.56	15.61	17.17	38.85	87.62	32.33	21.34
8	60	1	80	0	19.32	13.33	36.83	66.70	97.11	24.20	9.31
9	60	1	100	0	17.20	13.45	21.19	59.74	97.47	18.07	7.73
10	80	-1	80	0	19.31	16.37	17.26	41.98	92.15	23.74	17.77
11	70	0	90	1.6	20.58	13.27	17.98	43.13	86.46	39.64	27.52
12	80	1	100	3.2	16.71	13.17	14.64	61.89	97.38	21.17	12.51
13	60	-1	100	3.2	19.21	11.35	11.28	24.25	42.70	77.16	70.81
14	60	-1	100	0	27.26	14.00	14.87	46.68	70.63	68.61	56.96
15	70	0	100	1.6	18.97	12.56	15.71	30.38	75.02	46.57	45.14
16	70	1	90	1.6	14.16	11.32	18.44	54.43	99.14	6.20	3.39
17	80	1	80	3.2	15.65	13.53	13.21	63.58	98.06	18.24	8.82
18	60	1	80	3.2	25.74	13.07	27.35	71.85	97.25	20.24	11.62
19	70	0	90	3.2	18.00	12.73	12.46	40.16	85.61	44.00	31.31
20	80	0	90	1.6	17.96	14.14	13.30	42.66	90.00	33.98	24.33
21	80	-1	80	3.2	15.44	12.98	13.31	28.72	87.72	27.11	25.04
22	70	-1	90	1.6	20.57	12.93	13.32	35.79	73.48	57.09	48.08
23	60	0	90	1.6	24.59	14.87	14.23	42.55	72.55	62.33	50.79
24	60	-1	80	0	20.28	13.03	13.65	46.33	85.50	49.20	31.23
25	70	0	90	1.6	16.59	11.91	15.63	29.06	83.21	34.57	28.68
26	80	-1	100	0	20.44	15.40	21.59	34.00	82.93	34.23	28.49
27	80	1	80	0	18.02	15.73	35.88	74.76	99.60	5.38	1.82
28	80	-1	100	3.2	22.71	11.74	16.36	31.64	59.58	63.69	60.51

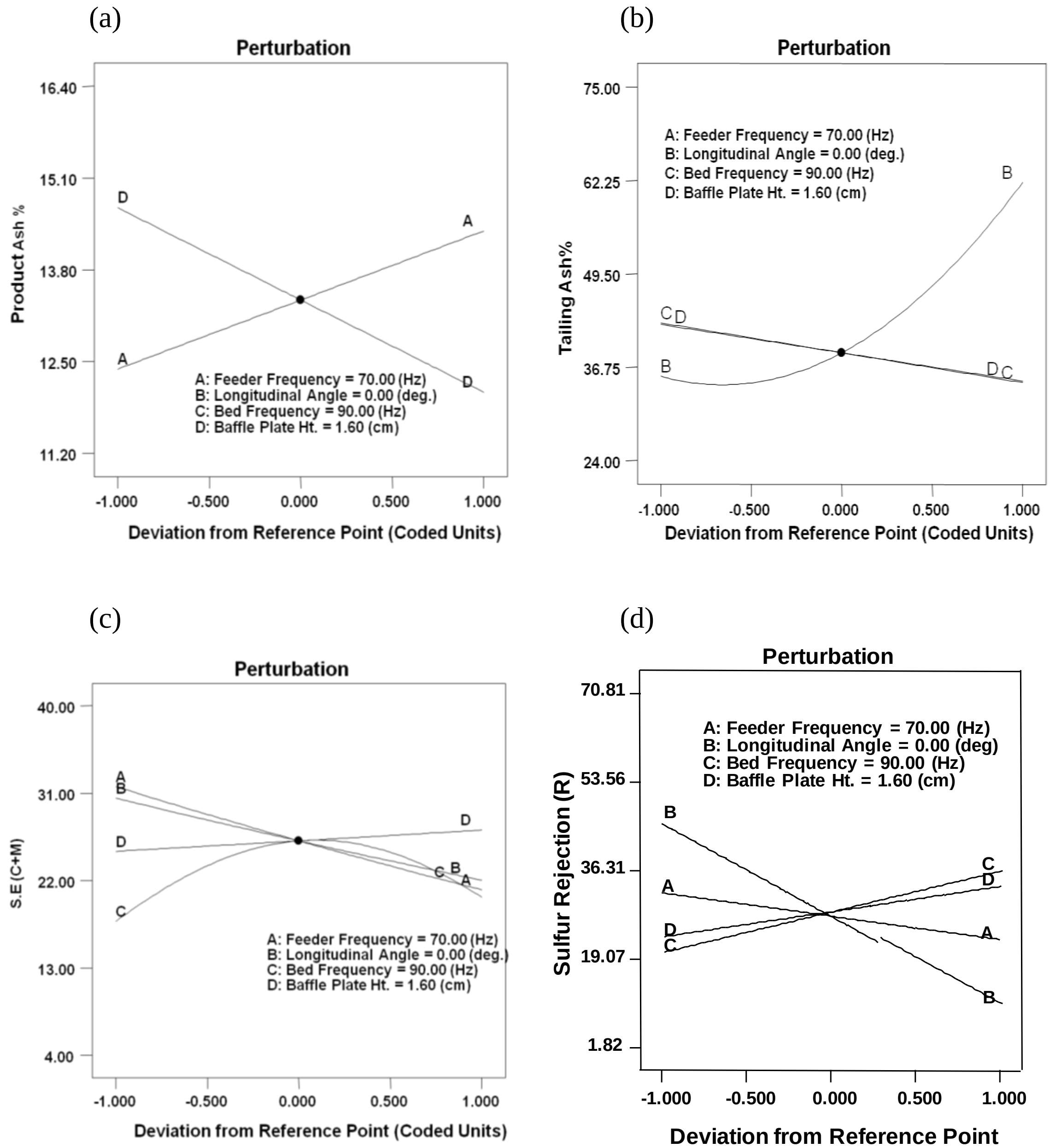


Figure 9: Perturbation plots for various process responses: (a) product ash content, (b) tailings ash content, (c) separation efficiency, and (d) sulfur rejection.

Empirical models were developed for three key process responses using the step-wise regression technique. It may be noted that tailings ash content response is the most critical performance parameter when deshaling is the primary purpose of the FGX Dry Separator application. As exhibited by the empirical model of Equation 1, tailings ash content was found to be a function of longitudinal deck angle, deck vibration frequency, and baffle plate height. Interaction effects of deck vibration frequency*baffle plate height and longitudinal angle*deck vibration frequency were also significant for the tailings ash response. Separation efficiency response is the most useful performance parameter when using the FGX Dry Separator to produce a final clean coal product. As indicated in Equation 2, the separation efficiency response was a function of all four key process parameters investigated in the optimization study. Parameter interaction effects significantly affecting separation efficiency included feeder frequency*baffle plate height and longitudinal angle*baffle plate height. All four key process parameters also contributed significantly to the sulfur rejection response, as indicated in Equation 3. Longitudinal angle*feeder frequency and longitudinal angle*deck vibration frequency were factor interactions significantly affecting the extent of sulfur rejection achieved by the FGX Dry Separator. The three empirical models were developed with R^2 values of 0.89, 0.90 and 0.97, respectively, and an overall F-ratio of <0.0001 in each case.

$$Tailings\ Ash = 38.73 + 13.24 * B - 4.09 * C - 3.87 * D - 2.46 * B * C + 2.33 * B * D + 10.04 * B^2 \quad [1]$$

$$\sqrt{Separation\ Efficiency} = 5.11 - 0.52 * A - 0.41 * B + 0.14 * C + 0.11 * D + 0.40 * A * D + 0.40 * B * D - 0.75 * C^2 \quad [2]$$

$$Sulfur\ Rejection = 27.41 - 4.57 * A - 17.98 * B + 7.93 * C + 4.89 * D + 1.96 * A * B - 6.41 * B * C \quad [3]$$

In these equations, A, B, C, and D are coded representations of feeder frequency, longitudinal deck angle, deck vibration frequency, and baffle plate height, respectively.

These model equations were utilized to simulate FGX Dry Separator performance for various operating conditions and to generate response surface contour plots shown in Figure 10. Figure 10(a) clearly shows that low feeder frequency (and thus, low feed rate), a lower level for baffle plate height, a low longitudinal angle, and medium level deck vibration frequency were conducive to high separation efficiency. However, if raw coal deshaling is the primary goal, tailings ash response has to be maximized. As shown in Figure 10(b), the highest tailings ash content can be obtained at high longitudinal angle along with low levels of deck frequency, feeder frequency, and baffle plate height.

Figures 10(c) and 10(d) indicate levels of sulfur rejection achievable for these two scenarios, i.e., for a high separation efficiency target versus a high tailings ash target. For the high separation efficiency target, high sulfur rejection of nearly 56% is achievable in the upper left corner of the experimental region. A slightly lower level of sulfur rejection (about 47%) is achievable in the specific experimental region that would result in the highest ash separation efficiency. When the objective is high tailings ash content, a lower level of sulfur rejection (not low tailings sulfur content) has to be tolerated.

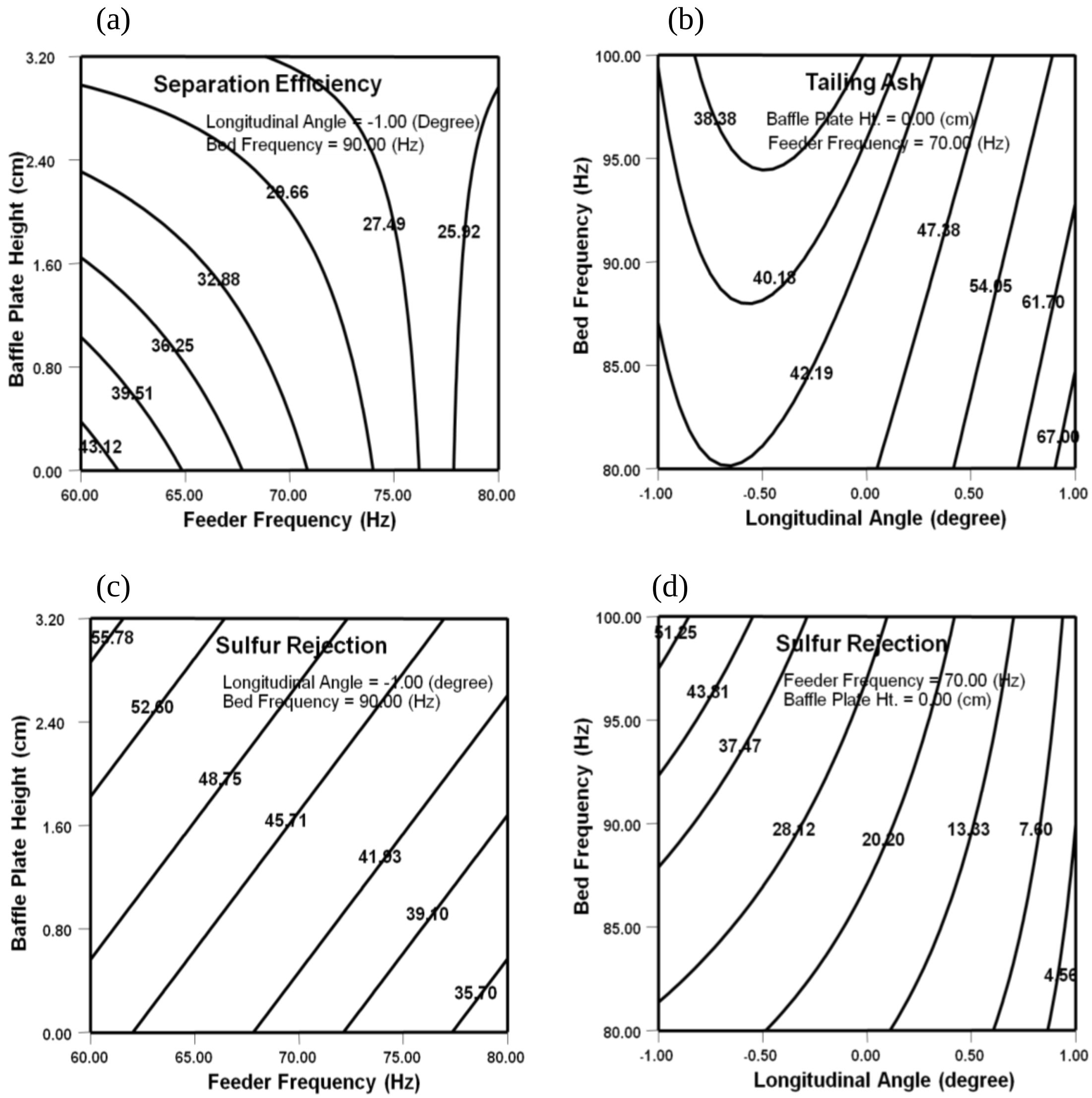


Figure 10: Simulated response surface contours generated with empirical model equations for: (a) separation efficiency, (b) tailings ash, (c) sulfur rejection with high separation efficiency as a target, and (d) sulfur rejection with high tailings ash as a target.

Task 3.4 Test Results for Multiple Coal Samples

Upon completion of a thorough evaluation of the FGX Dry Separator performance with the Knight Hawk Coal sample, four additional samples were obtained from other sources for testing. Selected test results obtained for each coal sample are summarized in Table 9. It should be noted that with the exception of the SIPC sample, these results were obtained by cleaning +4.76 mm coal. Due to its finer size, the SIPC sample was evaluated using the +1 mm size fraction.

Table 9: Results of expanded FGX-1 cleaning performance evaluation.

Knight Hawk Coal									
Ash %				Total Sulfur %				Yield %	
Feed	Product	Middlings	Tailings	Feed	Product	Middlings	Tailings	Product	Middlings
19.79	16.13	29.67	64.86	4.81	4.68	5.71	5.66	87.20	7.32
27.26	14.00	14.87	46.68	4.36	3.06	3.29	6.19	40.86	19.07
22.71	11.74	16.36	31.64	4.17	3.05	3.03	5.52	13.78	40.51
19.32	13.33	36.83	66.70	3.89	3.69	4.68	5.17	83.40	9.59
18.02	15.73	35.88	74.76	4.57	4.54	4.59	6.40	91.12	7.59
15.65	13.53	13.21	63.58	3.09	3.04	2.83	6.08	54.63	40.88
25.74	13.07	27.35	71.85	3.79	2.96	3.98	6.07	33.86	58.89
21.36	13.53	16.21	53.85	5.11	4.71	4.06	7.25	70.71	10.59
Springfield Coal									
Ash %				Total Sulfur %				Yield %	
Feed	Product	Middlings	Tailings	Feed	Product	Middlings	Tailings	Product	Middlings
29.05	16.91	56.03	88.39	3.89	3.77	3.79	4.72	79.53	7.70
42.88	17.65	46.08	89.26	4.52	3.91	4.04	6.12	50.99	22.85
40.06	15.24	51.88	88.16	4.28	4.23	2.78	6.47	52.28	27.50
42.36	16.33	30.55	80.83	5.13	4.08	4.66	6.66	38.70	26.87
30.84	14.39	45.60	82.53	4.33	4.07	3.76	6.21	65.15	19.77
28.23	15.49	47.61	89.90	4.66	4.16	5.41	7.09	74.02	15.59
34.45	13.48	39.57	85.09	4.68	3.87	4.62	6.87	58.07	19.90
36.79	27.12	84.00	84.58	4.64	4.58	4.83	6.377	83.00	16.12
33.16	21.56	81.14	92.07	4.00	4.00	4.01	4.138	80.93	16.89
Peabody Coal									
Ash %				Total Sulfur %				Yield %	
Feed	Product	Middlings	Tailings	Feed	Product	Middlings	Tailings	Product	Middlings
27.06	17.17	25.30	72.50	4.73	4.45	3.47	8.06	61.47	24.22
25.24	14.22	15.49	42.87	4.11	3.45	3.24	5.37	36.12	26.58
25.54	14.15	12.13	38.55	4.15	3.27	3.26	5.08	22.86	28.15
Phoenix Coal									
Ash %				Total Sulfur %				Yield %	
Feed	Product	Middlings	Tailings	Feed	Product	Middlings	Tailings	Product	Middlings
25.94	19.37	27.91	63.61	4.30	3.52	4.43	9.00	68.75	20.33
36.48	12.95	16.15	54.55	5.09	3.42	4.56	5.75	10.16	36.05
SIPC									
Ash %				Total Sulfur %				Yield %	
Feed	Product	Middlings	Tailings	Feed	Product	Middlings	Tailings	Product	Middlings
28.72	14.63	32.26	57.51	3.33	2.93	3.27	4.17	63.88	5.57
18.25	14.73	24.90	60.71	3.02	2.82	3.48	5.43	88.75	4.60

The best ash rejection and sulfur rejection results for all five coal samples are compared in Figures 11 and 12, respectively. Four of the five coal samples tested during this project originated from the Herrin No. 6 coal seam, Illinois' most prominent coal seam. Interestingly, variances in the cleaning characteristics for coals from different regions of the State are highlighted by performance differences exhibited in these two figures.

(a)

(b)

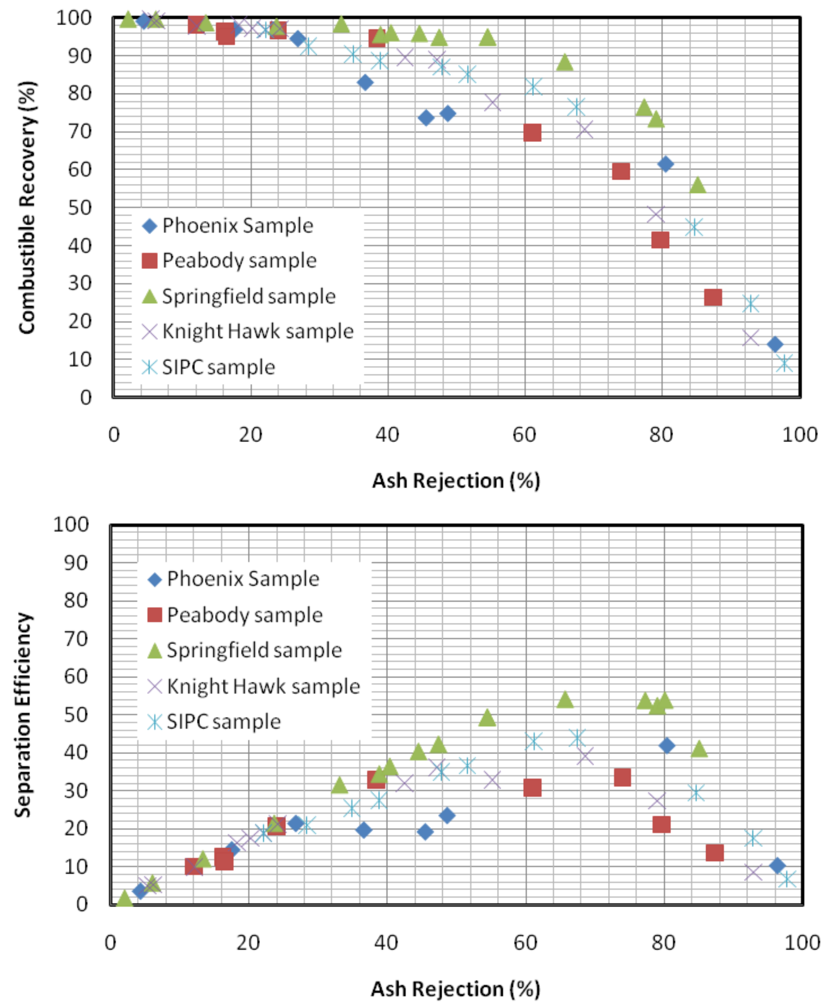


Figure 11: Model FGX-1 Dry Separator performance – ash rejection versus (a) combustible recovery and (b) separation efficiency.

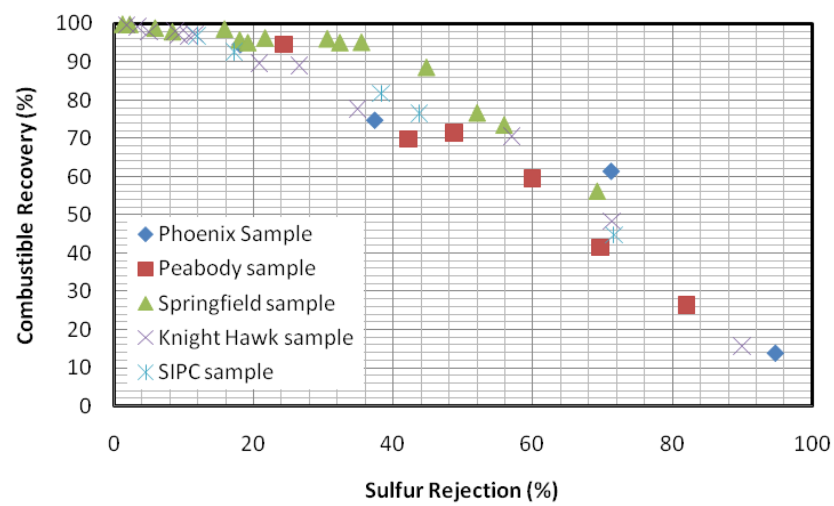


Figure 12: Model FGX-1 Dry Separator performance – sulfur rejection versus combustible recovery.

Of all the coal tested during this project, the Peabody Energy sample appeared to be the most difficult to clean, whereas the Springfield Coal sample was the easiest to clean coal. Maximum ash separation efficiencies achieved by the FGX Dry Separator were 53%, 44%, 42%, 39%, and 34% for Springfield Coal, SIPC, Phoenix Coal, Knight Hawk Coal, and Peabody Energy, respectively. Sulfur rejection achieved at low combustible recovery values were the highest for the Phoenix Coal sample. However, at a high combustible recovery setting of 80%, comparative sulfur rejection values were 50%, 44%, 42%, 36% and 28% for Springfield Coal, Knight Hawk Coal, SIPC, Peabody Energy, and Phoenix Coal, respectively.

It is generally believed that the FGX Dry Separator does not provide any effective cleaning below a particle size of about ¼-inch (6 mm). However, during this testing, comparable separation performance was achieved with the SIPC sample even though about 85% of it was in the 1 x 4.76 mm particle size range. Clearly, the bottom particle size limit for the FGX Dry Separator needs to be further investigated.

It is also generally believed that the presence of fines (-¼-inch size fraction) in the feed aids the separation process by facilitating the formation of a fluidized bed on the deck that serves as an autogenous dense medium. It was desired to investigate this hypothesis by conducting four series of experiments using the Knight Hawk Coal sample with varying proportions of fines (-4.76 mm size fraction). Ash rejection results are shown in Figure 13. They indicate that ash separation efficiency gradually increased as the proportion of fines increased from 0% to 29% at similar levels of ash rejection (~40%). However, examining combustible recovery versus sulfur rejection in Figure 14 suggests that at similar level of combustible recovery (~85%), the greatest sulfur rejection was achieved when the feed had only 18% fines. Therefore, further investigation is needed to establish an optimum proportion of fines in the feed. This study should also examine the relationship between fines proportions and cleaning indices and their influence (if any) on cleaning potential with the FGX Dry Separator.

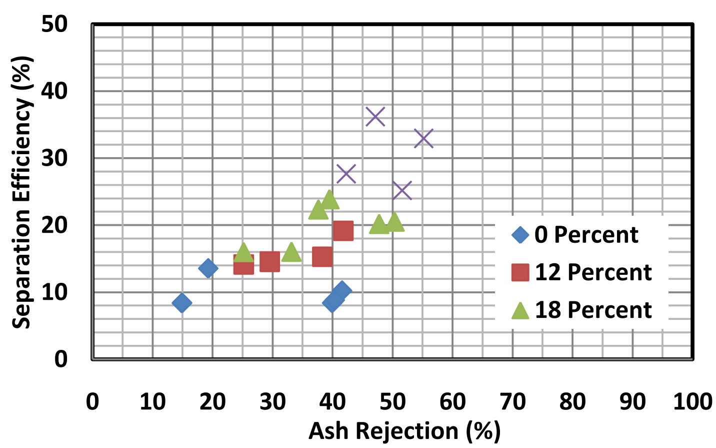


Figure 13: FGX Dry Separator ash cleaning performance with varying proportions of coal fines (-4 mesh) in the feed.

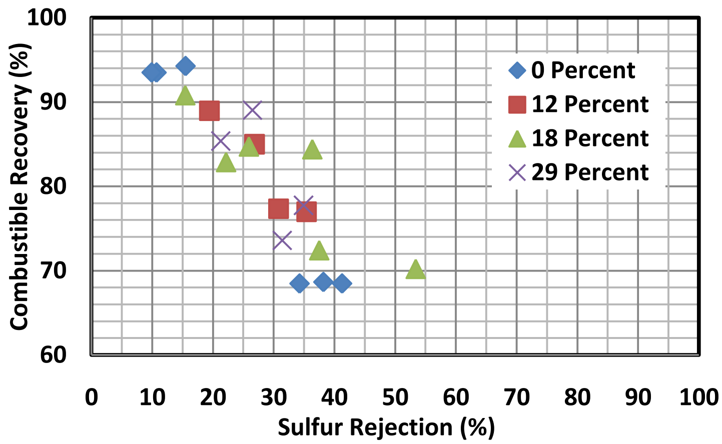


Figure 14: FGX Dry Separator sulfur cleaning performance with varying proportions of coal fines (-4 mesh) in the feed.

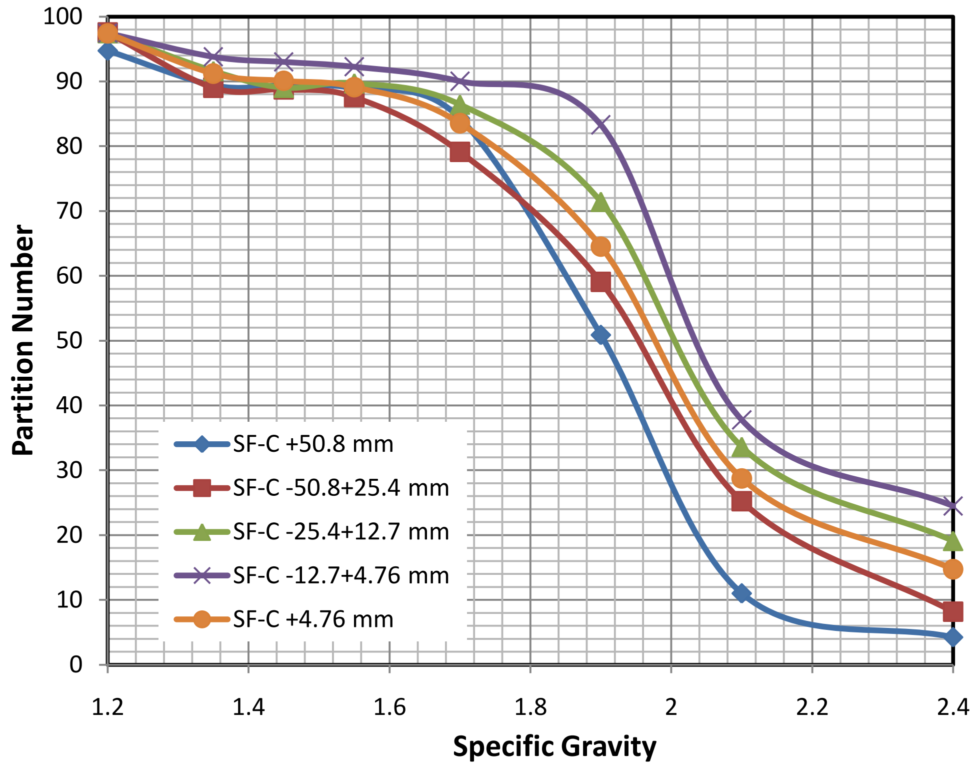
Task 3.5 FGX Dry Separator Partition Data

The cleaning efficiency of any density-based separator is evaluated by doing float/sink analyses on collected clean coal product and tailings samples and using the resulting data to generate partition curves. Partition data were generated for measuring the cleaning efficiency of the FGX Dry Separator by processing coals of four different size fractions, i.e., +2-inch (+50.8 mm), 2- x 1-inch (-50.8+25.4 mm), 1- x ½-inch (-25.4+12.7 mm), and ½-inch x 4 mesh (-12.7+4.76 mm). The overall (+4.76 mm) apparent partition curve for the Springfield Coal sample and apparent partition curves for each individual size fraction are shown in Figure 15(a). Effective specific gravity of separation (SG_{50}) and probable error (Ep) values obtained from these apparent partition curves are listed in Table 10. Apparent partition curves were corrected for clean coal bypass to tailings and high density reject bypass to product to generate corresponding corrected partition curves shown in Figure 15(b). Corresponding SG_{50c} and Ep_c values obtained from these corrected partition curves are also listed in Table 10 for comparison purposes.

Table 10: Size-by-size specific gravity of separation and probable error values for the Springfield Coal sample.

Test	Size Fraction (mm)	SG_{50}	Ep	SG_{50c}	Ep_c	Clean coal bypass to tailings (%)	Reject bypass to clean coal (%)
Springfield Coal	+50.8	1.90	0.12	1.90	0.11	5.25	4.23
	-50.8+25.4	1.95	0.18	1.94	0.16	2.47	8.19
	-25.4+12.7	2.01	0.19	1.98	0.11	2.57	19.1
	-12.7+4.76	2.03	0.23	1.99	0.08	2.54	24.49
	+4.76	**1.98**	**0.17**	**1.94**	**0.14**	**2.59**	**14.73**

(a)



(b)

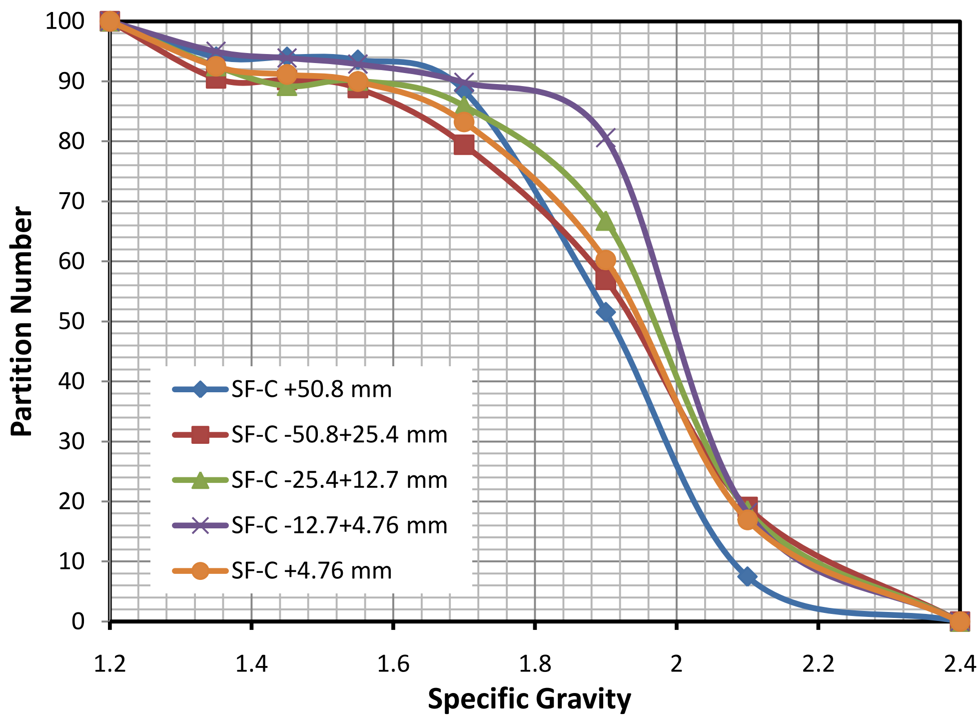


Figure 15: (a) Apparent and (b) corrected partition data for the Springfield Coal sample and for different size fractions of the same.

More insight into the cleaning performance achieved by the FGX Dry Separator was obtained by examining clean coal (1.6 SG float) loss to middlings and reject streams and recovery of reject material (2.0 SG sink) to clean coal product and middlings streams. These performance details are listed in Table 11 for two coals (Springfield Coal and Knight Hawk Coal) having distinctly different cleaning characteristics. As indicated previously in Table 9, tailings ash content of 85% was shown to be achievable for the Springfield Coal sample. This phenomenon is also evident in the small amount of clean coal loss (i.e., 2.54% of 1.6 float) in the tailings for the overall +4.76 mm size coal, as shown in Table 11. The amount of high density reject material (i.e., 2.0 sink) in the clean coal product was maintained at a reasonably low level of 3.73%. A simple analysis for the Springfield Coal sample would indicate that only about 0.42% of the entire clean coal present in the feed was lost to the tailings stream. Nearly 95.54% of the clean coal reported to the product stream and the remaining 4.04% reported to the middlings stream.

Mixing the middlings stream with either the clean coal stream or the refuse stream may be possible in some cases, based on target product specifications. However, analysis of the easy-to-clean Springfield Coal sample indicates the middlings stream contained 40.41% clean coal and 53.42% high density reject materials. Hence, the more desirable solution may be to clean the middlings stream a second time. Here it should be noted that direct recirculation of the middlings stream to the feed may not be the right option. Cleaning characteristics of the middlings coal will be significantly more difficult in comparison to the original feed. A simple analysis of data provided in Table 12 would indicate that the Cleaning Index (CI) for the Springfield Coal middlings stream was 0.43 in comparison to 0.72 for the original feed. Therefore, middlings coal should undergo a size reduction (i.e., crushing) step prior to being recirculated to the FGX Dry Separator feed stream. This should improve liberation characteristics of the middlings coal giving it a Cleaning Index similar to that of the original feed.

Table 11: Size-by-size separation efficiency data obtained from the FGX Dry Separator.

Size Fraction (mm)	FGX Feed (Weight %)	1.6 Float in Tailings (Weight %)	1.6 Float in Middlings (Weight %)	2.0 Sink in Clean Coal (Weight %)	2.0 Sink in Middlings (Weight %)
Springfield Coal with 0.72 Cleaning Index					
+50.8	5.61	5.31	39.55	3.23	56.23
-50.8+25.4	40.58	2.78	44.29	2.03	46.76
-25.4+12.7	30.91	1.17	40.34	4.16	54.16
-12.7+4.76	22.90	1.02	34.58	6.14	62.54
+4.76	**100.00**	**2.54**	**40.41**	**3.73**	**53.42**
Knight Hawk Coal with 0.53 Cleaning Index					
+50.8	5.71	30.64	58.78	0.00	18.26
-50.8+25.4	31.95	17.06	69.84	1.16	13.26
-25.4+12.7	26.69	5.27	68.87	5.67	22.24
-12.7+4.76	35.65	4.81	60.10	12.99	32.90
+4.76	**100.00**	**14.77**	**67.13**	**6.85**	**19.76**

Table 12: Float/sink data for feed and middlings coal from the Springfield Coal sample.

Springfield Coal	FGX Feed	FGX Middlings
SG	**Weight%**	**Weight%**
Float 1.3	53.86	28.09
-1.3+1.4	10.57	13.76
-1.4+1.5	8.51	18.50
-1.5+1.6	2.25	6.09
-1.6+1.8	2.33	0.45
-1.8+2.0	1.62	7.33
-2.0+2.2	1.14	5.02
2.2 Sink	19.74	20.76
Total	**100.0**	**100.0**

FGX Dry Separator performance data for a more difficult to clean Knight Hawk Coal sample, listed in Table 11, indicate greater amounts of high density reject material bypassing to the product (6.85%) and a significantly higher clean coal loss to the tailings stream (14.77%). For the two coarsest size fractions, clean coal loss to the tailings stream were 30.64% and 17.06%, which may be considered unacceptably high. More detailed analysis indicates that about 0.98% of the entire clean coal present in the feed was lost to the tailings stream. Approximately, 93.1% of the clean coal reported to the product and the remaining 5.92% to the middlings stream. For this type of coal, instead of losing a considerably high amount of clean coal to tailings, an option worth considering is to mix the tailings stream with the middlings stream and crush the resulting mixture to improve its liberation characteristics prior to cleaning it again using a second stage FGX Dry Separator. In other words, a rougher-scavenger type FGX Dry Separator circuit along with the above mentioned crushing operation would be recommended for relatively difficult to clean coal.

Task 4: Economic Analysis

A preliminary economic analysis was conducted to estimate the payback period as well as capital and operating costs required for commercial application of the FGX Dry Separator in cleaning Illinois coal. This economic analysis was based on information received from FGX SepTech, LLC following their recent experience with the first commercial installation of the FGX Dry Separator in the US (see Figure 16). Based on experimental data obtained for the Springfield Coal sample from the Model FGX-1 Dry Separator in Task 3, it can be inferred that a commercial Model FGX-12 Dry Separator can be used to produce 58.07 tph of clean coal having ash content of 13.48% and sulfur content of 3.87% by cleaning 100 tph of raw coal having ash and sulfur content of 34.45% and 4.68%, respectively. A schematic of this arrangement is shown in Figure 17.

Figure 16: First FGX Dry Separator commercial installation in the US by Buckeye Industrial Mining Company of Ohio (FGX SepTech, LLC, 2009).

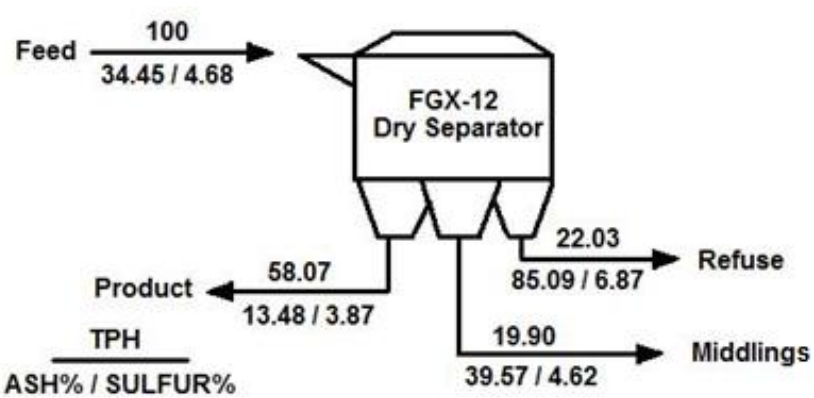


Figure 17: Schematic of proposed Model FGX-12 Dry Separator plant for processing easy-to-clean Illinois coal.

The following cost data was supplied by FGX SepTech, LLC (Zhao, 2009):

Capital and Installation Cost

Capital expenditure for a Model FGX-12 Dry Separator	$550,000
Capital expenditure for conveyor belts (feed, flat, radial stacker)	$141,000
Installation cost (including all civil and electrical work)	$191,000
Total capital and installation (CAPEX) costs	$882,000

Given a capital recovery factor of 0.1468 (12% rate of return and 15 year plant life), annualized capital and installation costs are estimated at $129,478.

Operating and Maintenance Cost

Total horsepower (HP) requirements for the Model FGX-12 Dry Separator are 432 HP including 335 HP for the blower fan motor, 50 HP for the draft fan motor, 30 HP for two vibratory motors, and 10 HP for the air compressor motor. The remaining horsepower is needed for conveyor belt motors. Based on experience at Buckeye Industrial Mining Company, the Model FGX-12 Dry Separator is expected to operate 120 hours per week for 50 weeks per year with two operators paid $25 per hour. Maintenance costs include regular deck rebuilds and replacing rubber liners. These estimates enable determination of the following operating and maintenance costs:

Cost	Per Week	Per Month	Annual
Energy		$9,000	$103,500
Labor	$6,000		$300,000
Maintenance			$ 10,000
Total operating and maintenance costs			$413,500

Therefore, annual ownership and operating costs for a Model FGX-12 Dry Separator operation are estimated at $542,978.

Payback Period

Assuming a minimum sales price of $30 per ton of clean coal and a product yield of 58.07%, annual revenue is calculated as follows:

Total raw coal cleaned per year: 6,000 hours x 100 tph	600,000 tons
Total clean coal produced per year: 600,000 x 0.5807	348,420 tons
Annual revenue:	$10.45 million

From this, the pay-back period is determined by dividing CAPEX costs by annual revenue. Thus, the pay-back period is estimated to be approximately one month.

FGX Dry Separator Costs Per Ton of Coal

From the above figures, the FGX Dry Separator unit cost can be estimated as follows:

Ownership Cost $= \frac{\$129{,}478}{600{,}000\ tons}$ = $0.22/ton of raw coal

$= \frac{\$129{,}478}{348{,}420\ tons}$ = $0.37/ton of clean coal

Operating/Maintenance Cost $= \frac{\$413{,}500}{600{,}000\ tons}$ = $0.69/ton of raw coal

$= \frac{\$413{,}500}{348{,}420\ tons}$ = $1.19/ton of clean coal

Thus, Total Ownership and Operating Cost = $0.91/ton of raw coal
= $1.56/ton of clean coal

The equipment vendor, FGX SepTech, LLC, claims that installation costs for future FGX Dry Separators can be significantly lowered based on experience gained from the first US installation. Therefore, for any FGX installations in Illinois, overall ownership and operating costs are expected to be lower.

Reject Disposal Cost

The above economic analysis was based on revenue generated from selling only the clean coal produced by the FGX Dry Separator. It did not account for any reject disposal costs. As shown in the schematic diagram of Figure 17, 22.03 tph of reject material having an ash content of above 85% and 19.90 tph of middlings material having an ash content of 39.57% is expected to be produced. Assuming $0.30 per ton-mile and 15 miles to the nearest landfill results in trucking costs of $4.50 per ton for hauling reject. This leads to annual reject disposal costs of $594,810 (22.03 x 6000 x 4.5).

Although reject disposal costs appear to be quite significant, they can be more than offset by further cleaning of the middlings stream and sale of the resulting product. Due to the close proximity of ash and sulfur content in middlings, product, and feed coal, it is sometimes mistakenly believed that the middlings stream can be directly recycled to the feed stream without affecting the cleaning performance of the FGX Dry Separator. However, as explained previously, it may be possible to render the middlings coal easier to clean by subjecting it to crushing.

A simple coarse crushing operation costing not more than $1.00 per ton of middlings coal may produce a feed coal of similar cleaning characteristics as that of the original feed. The crushed middlings coal may then be recirculated to the feed stream. This could increase total clean coal output by nearly 20% while maintaining clean coal quality and feed throughput at the designed level. In other words, a total of 69.63 tph (an additional 11.56 tph) of clean coal may be produced by cleaning 100 tph of raw coal and 19.90 tph of crushed middlings coal. Because the Model FGX-12 Dry Separator has a maximum feed handling capacity of 120 tph, it will not be overloaded when treating crushed middlings coal. This would result in additional operating costs of $119,400 per year ($1.0/ton x 19.9 tph x 6000 hours/year). However, processing the middlings stream in this fashion would produce additional revenue of $2,080,800 (11.56 tph x 6000 hours/year x $30/ton) for a net gain of $1,961,400.

Discounting the aforementioned reject disposal cost, a net additional income of $1.37 million may very well be generated by pursuing the middlings crushing and recleaning option. The resulting increase in revenue will lower the payback period to below one month. However, the resulting increase in cost due to crushing of middlings coal will marginally increase total cleaning cost from $1.56 to $1.58 per ton of clean coal in spite of the increased clean coal tonnage.

CONCLUSIONS AND RECOMMENDATIONS

The Model FGX-1 Dry Separator with feed throughput capacity of 10 tph was successfully evaluated at the Illinois Coal Development Park for its ability to clean five different types of coal. Coal samples were obtained from Knight Hawk Coal Company, Springfield Coal Company, SIPC, Peabody Energy, and Phoenix Coal Company. Important findings of this study are summarized as follow:

Conclusions

1. Of the eight FGX Dry Separator process variables investigated using the Plackett and Burman experimental design, four parameters had more significant effects on process responses such as combustible recovery, ash rejection, product ash and tailings ash content. These four process variables were feeder frequency, deck vibration frequency, clean coal gate (baffle plate) height, and longitudinal deck angle.
2. The optimization study conducted utilizing a Central Composite Design revealed the relative importance of these four key process parameters. Baffle plate height and feeder frequency affected product ash the most. Longitudinal deck angle affected tailings ash the most. Feeder frequency and longitudinal deck angle were the most significant factors contributing to ash separation efficiency. Deck vibration frequency and longitudinal deck angle affected sulfur rejection the most.
3. Maximum ash separation efficiency (combustible recovery – ash recovery) of 53% was achieved for the Springfield Coal sample having a Cleaning Index (CI) of 0.72. The best separation achieved for the Knight Hawk Coal sample, having a poor CI of 0.53, was only 39%. The maximum separation efficiency obtained for SIPC, Phoenix Coal, and Peabody Energy samples were 44%, 42% and 34%, respectively.
4. Sulfur rejection values obtained at a moderately high combustible recovery value of nearly 80%, were 50%, 44%, 42%, 36%, and 28% for Springfield Coal, Knight Hawk Coal, SIPC, Peabody Energy, and Phoenix Coal samples, respectively.
5. The presence of fines (-4.76 mm size coal) in feed ranging from 0 to 29% improved cleaning performance significantly. However, the highest ash separation efficiency was achieved at 29% fines, whereas the best sulfur rejection was achieved at a fines content of 18% in the feed.
6. The limited number of tests conducted with the relatively fine (93% of –4.76 mm particle size) SIPC sample indicated that reasonably good levels of ash and sulfur cleaning could be achieved by the FGX Dry Separator in the 4.76 x 1 mm size fraction.
7. The best density-based cleaning performance obtained from the FGX Dry Separator is described by SG_{50} and Ep values of 1.98 and 0.17, respectively, for +4.76 mm size coal. SG_{50} and Ep values for individual size fractions were as follow: 1.90 and 0.12 for the +50.8 mm size fraction, 1.95 and 0.18 for the 50.8 x 25.4 mm size fraction, 2.01 and 0.19 for the 25.4 x 12.7 mm size fraction, and 2.03 and 0.23 for the 12.7 x 4.76 mm size fraction.
8. For a relatively easy to clean Springfield Coal (CI: 0.72), only 0.42% of clean coal (i.e., 1.6 float fraction) present in the feed was lost to the tailings stream, whereas

95.54% was recovered to the product. For this type of coal, recleaning of the middlings coal following a size reduction step (to improve liberation) will most likely allow recovery of almost all clean coal to the product.

9. For a relatively difficult to clean Knight Hawk Coal (CI: 0.53), 93.1% of clean coal present in the feed was recovered to the product, whereas 0.98% of recoverable clean coal was lost to the tailings stream. For coal like this, a rougher-scavenger type of FGX Dry Separator circuit along with an intermediate crushing step for the rougher middlings and tailings streams would be recommended.
10. A preliminary economic analysis based on the technical data generated during this study and the installation and operating experience of a newly installed full-scale FGX Dry Separator in the US estimates total capital, installation, and operating costs for cleaning Illinois coal using the FGX Dry Separator to be $0.91/ton of raw coal and $1.56/ton of clean coal. The operating cost alone is estimated to be $0.69/ton of raw coal and $1.19/ton of clean coal. The payback period for a full-scale FGX Dry Separator having a feed handling capacity of 120 tph is estimated to be approximately one month.

Recommendations

1. The conventional belief is that the optimum particle size range for the FGX Dry Separator is 80 mm x 6 mm. However, reasonably good ash and sulfur cleaning was achieved from the FGX Dry Separator for 4.76 x 1.00 mm SIPC feed coal tested in this study. However, operating conditions were somewhat different than with larger size feed coal. It is also believed that some design modification may be necessary for the FGX Dry Separator to obtain an effective separation of fine coal in the particle size range of 6 mm x 1 mm.
2. While increasing the percentage of fines in the feed coal from 0 to 29%, it was observed that the cleaning performance of the FGX Dry Separator showed significant improvement. However, maximum levels of ash separation efficiency and sulfur rejection were achieved at different proportions of fine particles in the feed. Optimum percentages of fines in the feed and their relationship (if any) with the cleaning characteristics of the feed coal need to be further investigated.
3. The hypotheses put forward in Conclusions 8 and 9 relating to middlings recleaning and two-stage cleaning for more difficult to clean coals need to be verified by an experimental program.
4. A complete flowsheet for dry cleaning Illinois coal needs to be developed and demonstrated.

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